

## DC POWER SYSTEM FOR MARINE VESSELS

### CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. provisional patent application serial number 60/411,660 filed September 18, 2002, the entire contents of which are incorporated herein by reference.

### BACKGROUND

[0002] The invention relates to DC power systems and is related to U.S. patent application serial number 09/870,897, the entire contents of which are incorporated herein by reference, U.S. patent application serial number 10/186,768, the entire contents of which are incorporated herein by reference, U.S. patent application serial number 10/231,330, the entire contents of which are incorporated herein by reference and U.S. provisional patent application serial number 60/385,685, the entire contents of which are incorporated herein by reference.

[0003] The electric service on marine vessels typically comprises two or more diesel powered generators paralleled together on a common AC electric bus. While there is a great body of experience with conventional power plants in marine service, maintaining stability of an AC system is quite complex; all generators must remain in phase. AC generator stability issues include hunting, maximum power – pullout angle, effects of faults, out-of-phase transfers, and load transients. For best effect, generating

sources must be independent; AC generators in synchronization are not independent. Also, reactive AC, or the out-of-phase portion of the AC wave, does no useful work. Inherent to conventional marine power plants is the pervasiveness of reactive power that can reduce resulting voltage, heat equipment and wires, and waste energy.

## SUMMARY OF THE INVENTION

**[0004]** An embodiment of the invention is a power system for a marine vessel including a plurality of power sources. A propulsion power distribution unit is coupled to the plurality of primary power sources. A plurality of propulsion devices are coupled to the propulsion power distribution unit. A weaponry power distribution unit is coupled to the propulsion power distribution unit. A plurality of directed energy weapons are coupled to the weaponry power distribution unit.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0005]** Figures 1A and 1B depict a power system in one embodiment of the invention.

## DETAILED DESCRIPTION

**[0006]** Figures 1A and 1B depict a power system in an embodiment of the invention. The power system provides high availability (24 x 7 x forever), computer grade electricity to land based mission critical business and industrial processes. The system may be adapted for use on naval vessels to provide an electric infrastructure that greatly improves overall performance, reliability, and survivability.

[0007] The power system uses a redundant array of independent devices (“RAID”) architecture, to integrate multiple, independent, on-site power generators of any type (e.g., fuel cells, gas reciprocating engines, gas turbines, etc.), rotary power conditioners (motor generators), and flywheels by means of a water cooled DC link to create an ultra reliable, computer grade power system. The power system technology includes rectifier topology, failsafe controls, a DC disconnect capable of interrupting 6k amps without arcing, and a unique over voltage protection device. The power system has no single point of failure and is extremely fault tolerant. The science of probabilistic risk assessment (“PRA”) determines the number of redundant components in a specific installation. The design balances redundancy against the inherent problem of complexity to arrive at an optimal and simple system design.

[0008] Referring to Figure 1A, primary power sources 20 generate AC power that feeds a propulsion power distribution unit. Primary power sources 20 may be any known power source such as fuel cells, gas reciprocating engines, gas turbines, etc. The propulsion power distribution unit includes two DC rails 22 and 24 coupled by rungs 26A, 26B and 26C. Each rung 26 is fed power by each of the primary power sources 20 through AC-DC converters 28. The power system takes the AC output of each primary power source 20 into separate, independent rectifiers and changes the power to DC that supplies the dual rail, DC propulsion power distribution unit. Voltage on the DC link system is tightly controlled (e.g., to 550 volts). Each rung 26 is coupled to a propulsion motor 30 which imparts motion to the vessel. Within each rung 26, disconnects 32 straddle feeds in and out of the rung 26. This allows components or even an entire rung 26 to be isolated for service, upgrade, etc.

[0009] Using a DC propulsion power distribution unit eliminates the issues of paralleling AC outputs from multiple generating sources, takes away the possibility of single points of failure, and eliminates inter-dependencies among generation sources, negating the potential for cascade failures. Reverse power flow may be blocked by diodes; low voltage or phasing on one generating source cannot affect others. The DC propulsion power distribution unit allows independent control of real power from each source thereby eliminating reactive power issues at the generator.

[0010] The DC propulsion power distribution unit provides DC power to a weaponry power distribution unit. The weaponry power distribution unit includes two DC rails 42 and 44 coupled by rungs 46A, 46B and 46C. Each rung 46 is fed power by one of rungs 26A-26C through DC-DC converters 48. Each rung 46 is coupled to directed energy weaponry 50. Within each rung 46, disconnects 52 straddle feeds in and out of the rung 46. This allows components or even an entire rung 46 to be isolated for service, upgrade, etc. An energy storage device 54, such as a superconducting magnetic energy storage device, is coupled to each rung 46.

[0011] The DC propulsion power distribution unit is also connected to an auxiliary power distribution unit shown in Figure 1B. The auxiliary power distribution unit includes two DC rails 62 and 64 coupled by rungs 66A-66G. Rung 26B is coupled to rung 66B through DC-DC converter 68A. Rung 26A is coupled to rung 66D through DC-DC converter 68B. Rung 26C is coupled to rung 66F through DC-DC converter 68C. Each rung 66 also receives power from multiple auxiliary power sources 70 which generate AC power and are coupled to one or more rungs 66 through AC-DC converters 72. Auxiliary power sources 70 may be any known power source (e.g., fuel cells, gas

reciprocating engines, gas turbines, etc.). AC loads 74 may be connected to each rung through DC-AC converters 76 (e.g., motor-generators). DC-AC converter 76 output may be 480 VAC with the voltage tolerance parameters that IEEE Standard 446-1987 specifies for computer equipment. The DC-AC converter 76 clears faults and handles inrush current demands from the loads. The DC-AC converters 76 also supplies reactive power close to the load allowing the prime generating sources to operate at a high power factor. Solid state variable speed drives may be used to convert the 550 VDC to 480 VAC for powering chillers, fans, and pumps.

[0012] DC loads 78 may be connected to each rung through DC-DC converters 80. DC-DC converter 80 may be employed to buck the DC link voltage to 48 VDC at the point of use for telecom loads.

[0013] Within each rung 66, disconnects 82 straddle feeds in and out of the rung 66. This allows components or even an entire rung 66 to be isolated for service, upgrade, etc. Ancillary power sources 84 (e.g., flywheels, batteries) are coupled to one or more rungs 66 to stabilize system voltage and mitigate the effects of faults, generating source failures, and load transients.

[0014] Each load, whether DC or AC, is isolated from other system outputs by AC-DC converter or DC-DC converter. Therefore, an electrical event on one circuit cannot propagate to any other circuit.

[0015] While at sea in non-combat conditions, in addition to powering the main propulsion motors 30 via the 20 kVDC propulsion power distribution unit, the primary power sources 20 supply power to the 600 VDC auxiliary power distribution unit and the weapon power distribution unit. During battle conditions the auxiliary power sources 70

would be brought on line so that all of the power from the primary power sources would be available to the main propulsion motors 30 and directed energy weaponry 50.

[0016] The energy storage device 54 supplies high intensity power bursts to the directed energy weapons 50, which could be high-energy microwave or laser based weapons. Energy storage device 54 may be charged using regenerative braking techniques. While in port, the primary power sources 20 are shut down and an appropriate number of auxiliary power sources 70 supply power requirements. The number of primary power sources 20 and auxiliary power sources 70 depends upon the redundancy needed to achieve the desired level of availability.

[0017] The power system of Figures 1A and 1B allow compact power sources such as rotary engines to be used for the auxiliary power sources 70. The auxiliary power sources 70 as well as the primary power sources 20 may be disbursed strategically throughout the ship. This enhances survivability; power would be available to both parts even if the ship were to be cut completely in two. In an emergency, the system can be configured so that the main propulsion motors 30 are powered from the auxiliary power distribution unit, albeit at a reduced power rating. By using the DC systems described herein, ship designers realize significant space and weight savings in a vessel's electric infrastructure while effecting a substantial improvement in reliability, availability, and survivability.

[0018] The power system does not subscribe to an "N+2" or similar simplistic redundancy criteria. The power system is designed to meet specific availability and reliability requirements, and to eliminate single points of failure. Redundant units are added as required based on the PRA evaluation. Units that fail more frequently (e.g.,

engine generators) will require a larger degree of redundancy than more reliable components (e.g., motor generators). Simplistic "N+1" or "2N" redundancy criteria typically spend far too much on some redundant systems while simultaneously providing too little redundancy for others. The result is a needlessly complex system that costs more, is difficult to operate and maintain, and as a result is more likely to fail. In embodiments of the power system, redundancy is balanced against the inherent problem of complexity to arrive at a system design that meets system requirements at a minimum cost. The quantitative approach to this area results in the user being able to make informed decisions about redundancy, spare parts inventory, operating tactics, service agreements, and staffing levels.

[0019] The propulsion power distribution units may be implemented using a superconducting DC bus operating at +/- 10 kV and up to 10 kA. This bus is suitable for conveying power from multiple remote sources to the ship's drive systems and to the various directed energy weapons 50 and energy storage device 54. The bus design includes cooling and thermal management systems. Emphasis may be placed on making the bus small, rugged, and requiring extremely little or no maintenance throughout its operating lifetime.

[0020] Rectifiers and inverters employed in AC-DC converters, DC-AC converters and DC-DC converters in the power system may use SCR technology because of the technology's proven field reliability and extraordinary ruggedness. The power system may use water cooling to minimize module size and weight. Cryogenic cooling (typically with liquid nitrogen, to 77 degrees Kelvin) offers several potential advantages for DD(X) applications. First, cryogenic cooling reduces resistive losses in copper

components by a factor of six, resulting in improved efficiency at the high drive power levels, and/or substantially reduced footprint by virtue of greatly reduced electrical interconnect size.

[0021] Second, cryocooling offers the potential of allowing the SCRs to handle extremely large momentary overloads, as the maximum junction temperature limits will remain unchanged at approximately 400 Kelvin. When cooled at or near room temperature, junction temperature rise during an electrical fault or pulsed power operation (for firing directed energy weapons 50) is limited to at most 100 Kelvin. With cryogenic cooling, the maximum junction temperature rise will exceed 300 Kelvin. The SCR's ability to safely conduct such large overloads will allow the rectifiers to electronically control faults, continue to operate with some devices damaged or destroyed, while the good heat transfer characteristics of boiling liquid nitrogen permits a rapid recovery to normal operating temperatures.

[0022] Third, cryocooling substantially reduces the difficulty of connecting hot power sources to a superconducting bus and superconducting motors. Cryocooled rectifiers and motor drives operate between the room temperature equipment and the superconducting materials. Their large cold mass and relatively small conductor cross-sections (enabled by the 6x reduction in copper resistivity) greatly simplify the design of the transition to superconducting temperatures, and reduce consumption of precious liquid helium.

[0023] Disconnects 32, 52 and/or 82 may be implemented using cryogenically cooled arcless DC switches and circuit breakers. The power system may include DC switches rated at 6 kA and capable of interrupting full rated current with no arc. This

technology may be extended to cryogenic rectifiers and superconducting DC bus. Existing switches have a size of 32"x24"x18", approximately 1/10 the volume of conventional switches utilizing arc chutes. Cryogenic cooling could further reduce the size (although mechanical forces developed by large fault currents may limit the amount of reduction possible) and will certainly extend the maximum permissible fault current that the device can safely interrupt.

**[0024]** While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto without departing from the spirit and scope of the invention. Accordingly, it is to be understood that the present invention has been described by way of illustration and not limitation.